Numerical Modelling of Piled Raft Foundation in Soft Clays

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ABSTRACT

In the conventional design for load capacity of piled raft foundations, the piles are assumed to carry the total structural load ignoring any contribution from the raft. The current lack of efficient and reliable design methods for piled rafts, has resulted in conservative estimate of the foundation performance, and therefore, over design of the foundation. A few researchers have investigated the effect of number of piles, pile length and stiffness of the raft on the performance of piled raft. However, understanding of the interaction between pile, raft and the soil is complex and still limited. This is especially true when the foundation is constructed over soft or loose ground which provides little bearing to the raft. In this paper, a piled raft with 2x2 pile group in soft soil is modelled using 2-D finite element tools. Use of these numerical approaches help validate simple problems using least computational effort. Parametric study was conducted by varying the pile length, spacing between the piles and stiffness of the raft. The results seem to indicate that small rafts over soft soils have little effect on vertical load capacity when friction piles are used.

1. INTRODUCTION

The problem of the design of piled raft foundation has become important over the past few decades because of more and more large structures being built on weak ground. At the 13th ICSMGE in New Delhi in 1994, Professor Mark Randolph presented his state-of-the-art paper on pile groups and piled rafts. Since then there have been many studies and significant improvement in the engineering practice applied to the determination of the load capacity of piled raft foundation (Poulos 2001, Horikoshi & Randolph 2001, Ta & Small 2006, Poulos & Bunce 2008). Differential settlement of the piled raft can decrease with the increase in pile length or increase in the number of piles since lesser loads will then be carried by the raft. However, literature suggests that by having more piles does not always produce the best foundation performance. For instance, it was observed that the relative settlement was reduced to less than half when the length of the piles was doubled (Katzenbach 1998). The pile load in piled-raft increased with the increase in the number of piles but there was an upper limit to the number of piles beyond which very little additional benefit was obtained (Poulos 2001). The maximum settlement of the piled raft was found to decrease only up to a limit upon the increase in the number of piles.

It was observed that the ratio of width of the pile group and width of the raft, \( B_p/B_R \) of unity was shown to minimize the average settlement, whereas \( B_p/B_R \) of 0.5 helped to minimize the differential settlement. Other factors which can affect the performance of piled raft are configuration of piles within the group and raft thickness. The first factor is difficult to quantify since it depends upon the loading conditions and is site specific (Kim et al. 2001, Bezerra et al. 2005). The second factor controls rigidity of the raft and hence the differential settlement of the raft. Most of the case histories deal with piled raft constructed either over stiff clays or medium to dense sands which provide adequate bearing stratum for the raft (Poulos & Bunce 2008). Little literature is available on the performance of piled raft constructed over soft clays.

In the present study, the load capacity of piled raft installed in soft clay is calculated using simplified and numerical methods. Bored cast-in-situ piles were used in the analysis. It is assumed that the construction of bored piles would cause minimum disturbance to the surrounding soil and hence soil properties before and after the construction of the piles were assumed to be unchanged. Commercially available finite element software PLAXIS v8 was used in this work (Brinkgreve et al. 2006). Although three-dimensional (3D) rigorous analysis would best suit this method is useful to validate simple problems using least computational effort. The effect of pile length and spacing on settlement of the raft is investigated. Results are found to be encouraging when compared to the findings of the other researchers.
2. METHOD OF ANALYSIS

Site investigation data was collected from Hazira, District Surat in India where large industrial development is to take place. Table 1 shows the typical soil profile and properties available at the site. In general, the site consists of soft marine clay sandwiching a 4m thick fine sand layer at about 8.3m depth. The marine clays extent up to 15.5m depth below which lie medium to dense sands and gravels.

The second layer of cohesionless deposits extended up to 30m depth. Ground water table exist at about 3m below surface. Stiffness of the soil was not directly available but interpreted from the SPT values. It was desired to utilize the bearing capacity available at the surface and at the same time the friction resistance of the piles. The piled raft foundation was modelled using PLAXIS v8 FE program using 15-node triangular elements to model the soil (Brinkgreve et al. 2006). Raft with 2x2 pile group was used in this study. Width and thickness of the raft, length and spacing between the piles in the group, were the variables in this study.

Table 2 shows the different parameters used in this study. Because of symmetry, only one half of the foundation was modelled. Clearly, the geometry of this construction is a 3D problem and not idealized plane strain with equivalent piled wall otherwise used in this study. Notwithstanding this, the two-dimensional (2D) geometric idealization is useful to validate simple problems using least computational effort. Concrete raft and piles were modelled using beam elements with interface elements provided along the length of the piles. Beam elements have the advantage in that both shearing force and bending moments can be prescribed. One possible drawback is that beam element cannot be discretized and therefore may not correctly model thick concrete elements such as raft, but this effect was minimized by modelling of beam above the ground level as shown in Figure 1. The soils were modelled using elastic perfectly plastic Mohr Coulomb failure criteria.

![Fig. 1: Finite Element Idealization of Pile Raft Element](image)

### Table 1: Soil Profile and Available Data

<table>
<thead>
<tr>
<th>Soil description</th>
<th>Depth (m)</th>
<th>Soil Data</th>
<th>SPT-N</th>
<th>Stiffness E (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Clay</td>
<td>0 – 2.2</td>
<td>(\gamma_{dry} = 11.7 \text{kN/m}^3, \gamma_{sat} = 16.4 \text{kN/m}^3, c = 20 \text{kN/m}^2, \phi = 16^\circ, \nu = 0.27)</td>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>Marine Clay</td>
<td>2.2 – 4.5</td>
<td>(\gamma_{dry} = 14.2 \text{kN/m}^3, \gamma_{sat} = 20.4 \text{kN/m}^3, c = 13 \text{kN/m}^2, \phi = 19^\circ, \nu = 0.27)</td>
<td>3</td>
<td>1500</td>
</tr>
<tr>
<td>Soft to Stiff Marine Clay</td>
<td>4.5 – 8.3</td>
<td>(\gamma_{dry} = 12.8 \text{kN/m}^3, \gamma_{sat} = 17.7 \text{kN/m}^3, c = 13 \text{kN/m}^2, \phi = 28^\circ, \nu = 0.3)</td>
<td>13</td>
<td>6500</td>
</tr>
<tr>
<td>Loose to medium fine sand</td>
<td>8.3 – 12.4</td>
<td>(\gamma_{dry} = 14.6 \text{kN/m}^3, \gamma_{sat} = 18.5 \text{kN/m}^3, c = 3 \text{kN/m}^2, \phi = 28^\circ, \nu = 0.27)</td>
<td>20</td>
<td>10000</td>
</tr>
<tr>
<td>Medium Plastic Clay</td>
<td>12.4 – 15.5</td>
<td>(\gamma_{dry} = 15.1 \text{kN/m}^3, \gamma_{sat} = 18.8 \text{kN/m}^3, c = 20 \text{kN/m}^2, \phi = 21^\circ, \nu = 0.3)</td>
<td>21</td>
<td>11000</td>
</tr>
<tr>
<td>Clayey Sand and Gravel</td>
<td>15.5 – 20</td>
<td>(\gamma_{dry} = 15.6 \text{kN/m}^3, \gamma_{sat} = 19.1 \text{kN/m}^3, c = 10 \text{kN/m}^2, \phi = 10^\circ, \nu = 0.27)</td>
<td>50</td>
<td>25000</td>
</tr>
</tbody>
</table>

### Table 2: Geometry Parameters Used in This Study

<table>
<thead>
<tr>
<th>Raft Size</th>
<th>Raft Thickness (m)</th>
<th>Pile Diameter (m)</th>
<th>Pile Length (m)</th>
<th>Pile Spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5m x 5m</td>
<td>0.3, 0.6, 1, 1.5, 2</td>
<td>0.3</td>
<td>6, 9 and 12</td>
<td>1, 2, 2.5, 3, 5</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

Effect of Raft Thickness
In this step, the piled raft with 2x2 pile group was modelled for pile length 6m and pile spacing of 2m centre to centre. The allowable load calculated for this foundation was 90kN/m² and was applied over the raft. As shown in Table 2, the raft thickness was varied between 0.3 and 2m in different tests. As the figure shows, the change in thickness of the raft did not affect the total settlement and the maximum settlement was about 65.5mm in all. As the raft thickness was increased, normalized settlement was nearly constant.

Figure 2 also shows that the differential settlement was negligible and was less than 1:3000 for the 300mm thick raft which is less than that prescribed for shallow foundations. This was expected because of the small size of the raft.

![Fig. 2: Settlement Due to Change in Raft Thickness](image)

Effect of Pile Length
The effect of pile length on the piled raft was studied for the settlement of raft for three different lengths of piles as 6m, 9m and 12m. In this analysis, the raft thickness was 1m and the spacing between the piles was taken as 2m. The pile diameter was taken as 0.3m for all pile lengths. Allowable load intensity of 90kN/m², 150kN/m² and 240kN/m² was applied for pile groups of length 6m, 9m and 12m, respectively. The effect of length of pile on settlement of piled raft under allowable load is shown in Figure 3. It can be seen that the overall settlement of the foundation increased as the pile length was increased. However, the differential settlement was still observed to negligible. The load deformation curves up to failure for different pile lengths were also observed in these tests. The load applied was much higher than the allowable load. From the Figure 4 it can be observed that with the increase in length of the piles, the load taken by the foundation also increases. Even though the load capacity of the raft alone can be read directly from the figure, it remains to be seen that load settlement curve of the raft alone is comparable compared to that taken by the piles.

![Fig. 3: Effect of Pile Length on Settlement of Piled Raft](image)

Effect of Pile Spacing
The effect of pile spacing was studied for the piled raft foundation with fixed raft width of 1m and pile length of 6m. The pile spacing was taken as 1m, 2m, 3m and 5m for the load intensity of 90kN/m². The piles were 0.3m in diameter. When the load was applied, the reduction in pile spacing had the effect of reducing the raft settlement. From Figure 5 it can be seen that as the spacing reduces, which means when the piles are more concentrated to the centre, the average settlement is found to be increase while when the pile spacing is more, as piles are oriented outward the average settlement is less.

![Fig. 4: Load Settlement Curve for Different Pile Lengths](image)
Horizontal Pile Deflection Due to Vertical Loading

The effect of horizontal pile deflection due to vertical loading on the piled raft was also observed. The raft thickness was taken as 1m and the pile length of 6m pile with diameter of 0.3m was taken for modeling. The spacing between the piles was varied from 1m, 2m, 3m and 5m. The load intensity was maintained equal to 90kN/m² for all 4 cases. From the Figure 6 it can be observed that the horizontal displacement in piles increased with the increase in pile spacing. Pile deflection also appears to change with increase in pile spacing. The piles deflect away from the centre of the raft as the spacing increased. Horizontal displacement in piles was the maximum at the middle of the piles and then it was noted to decrease towards the end.

Fig. 6: Horizontal Displacement of Pile Due to Vertical Loading

4. CONCLUSION

Studies and analysis conducted on un-piled raft and piled raft foundation list the following conclusions.

1. Under the working load intensity of 90kN/m², maximum settlement for raft of size 5m × 5m and thickness 0.25m with the piles of diameter 0.3m and pile size 6m is 66mm. Increasing the raft thickness decreased the overall settlement of the piled raft foundation. The corresponding values of settlements for the raft thickness of 0.6m, 1m, 1.5m and 2m are 65.6, 65.4, 65.5 and 65.4 respectively.

2. The settlement of the piled raft foundation increased with increase in the pile length. When the pile length varied as 6m, 9m and 12m the overall settlements observed were 70mm, 89mm and 136mm respectively. Pile load increased from 130kN/m² to 300kN/m² for increase in pile length.

3. Under load intensity of 90kN/m² and pile spacing in between 1m and 5m, the maximum settlement was in between 53mm and 80mm respectively.

4. The horizontal pile deflection due to vertical loading on the piled raft was also observed. When the pile spacing was varied as 1m, 2m, 3m and 5m, the maximum horizontal displacements were observed as -1mm, 8mm, 9mm and 13 mm respectively.

REFERENCES


Poulos, H.G and Bunce, G. (2008). Foundation design for the Burj Dubai – the world’s tallest building. 6th International Conference on Case Histories in Geotechnical Engineering, 1-47.
